SPONTANEOUS LORENTZ VIOLATION AND BARYOGENESIS

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In the presence of background fields that spontaneously violate Lorentz invariance, a matter-antimatter asymmetry can be generated even in thermal equilibrium. In this paper we systematically investigate models of this type, showing that either high-energy or electroweak versions of baryogenesis are possible, depending on the dynamics of the Lorentz-violating fields. We identify two scenarios of interest: baryogenesis from a weak-scale pseudo-Nambu-Goldstone boson with intermediate-scale baryon-number violation, and sphaleron-induced baryogenesis driven by a constant-magnitude vector with a late-time phase transition.

1. Introduction

The observed universe manifests a pronounced asymmetry between the number density of baryons n_b and antibaryons $n_{\bar{b}}$. However, the origin of the baryon number asymmetry remains a major puzzle for cosmology and particle physics. In a classic work, Sakharov argued that three conditions are necessary to dynamically generate a baryon asymmetry in an initially baryon-symmetric universe: (1) baryon number non-conserving interactions; (2) C and CP violation; (3) departure from thermal equilibrium. In deriving these conditions, the assumption is made that CPT is conserved. If Lorentz invariance is violated, then CPT is also violated, one can generate baryons in thermal equilibrium. This idea is first implemented in the context of "spontaneous baryogenesis"[1] scenario and has subsequently been elaborated upon in various ways [2,3,4,5,6,7,8].

In most of the previous studies, the effects of sphaleron transitions are not discussed or mistakenly believed to wash out the baryon asymmetry if $B-L$ is zero. The role of sphaleron transitions in thermal equilibrium is to

adjust different particle density distributions in a way that preserves $B-L$ to minimize the total free energy. In the presence of a Lorentz-violating background, the one particle free energy is modified and final net baryon number density should be quite different from the one without Lorentz-violating background. In this situation, sphaleron transitions will generate a nonzero $B+L$. Because of that, we reconsider previously studied models and construct new models[9]. We find the final net baryon number density largely depends on how the effective chemical potential ga_0 evolves with time. This provide us a general rule to categorize different models of baryogenesis via spontaneous Lorentz violation and understand them in a unified picture. We also identify two scenarios of potential interest. One is the case of a simple constant-magnitude timelike vector field coupled to J^μ_{B+L} where appropriate baryon asymmetry could be generated by electroweak sphalerons alone and the other is that of a derivatively-coupled pseudo-Nambu-Goldstone boson with a weak scale mass and $(B-L)$-violating interactions are freeze out at Majorana neutrino mass scale of order 10^{10} GeV.

2. Baryogenesis in the presence of Lorentz violation

We consider the theory of a vector field A_μ with a nonzero vacuum expectation value (vev), coupled to a current J^μ in the matter fields which corresponds to some continuous global symmetry. The vector field gets a condensate $A_\mu = (a_0, 0, 0, 0)$ and that makes the interaction term $\mathcal{L}_{int} = gA_\mu J^\mu \to -ga_0 Q$, where Q is the conserved charge. Such an interaction term now acts like a "chemical potential" $\mu_b^0 = ga_0$ for the matter fields, which splits the free energy of particle and anti-particle. Because of this effect, there will be a non-zero baryon number density generated by baryon-number violating interactions in thermal equilibrium $n_B = n_b - n_{\bar{b}} = g_b T^3 \left[\pi^2 \frac{\mu_b^0}{T} + \left(\frac{\mu_b^0}{T}\right)^3\right]/6\pi^2 \simeq g_b \mu_b^0 T^2/6 \sim \mu_b^0 T^2$, where g_b counts the internal degrees of freedom of the baryons. When the B-violating interactions mentioned above become ineffective ($\Gamma \leq H$), we get the final baryon asymmetry

$$\frac{n_B}{s} \sim \frac{\mu_b^0}{g_{*s} T_F} = \frac{ga_0}{g_{*s} T_F}\,, \tag{1}$$

with the entropy density $s = (2\pi^2/45) g_{*s} T^3$, where T_F is the temperature at which the baryon number production is frozen out.

With such a spontaneous Lorentz violation background, the energy dispersion relation is modified to $E = \sqrt{K_i^2 + m^2} \pm \mu^0$, where K_i is the momen-

tum of the fermion and $\pm$ are for fermion and anti-fermion respectively. The net baryon number density now becomes $B^{(\mu)} = -\frac{2N}{13}T^2(3\mu^0 + \frac{1}{N}\sum_{i=1}^{N}\mu_i^0)$, where the parameters μ and μ_i are the chemical potentials of the quarks and the ith lepton, respectively. If there is leptonic flavor violation in thermal equilibrium, one can write it in terms of $\mu_L^0 \equiv \dfrac{1}{N}\sum_{i=1}^{N}\mu_i^0$ and $\mu_B^0 = 3\mu^0$. The fact that $B \propto (\mu_B^0 + \mu_L^0) = 2\mu_{B+L}^0$ tells us a nonzero net baryon number density can be spontaneously generated through sphaleron transitions in thermal equilibrium in the presence of a nonzero time-like vector background coupled to J_{B+L} current.

As we know sphaleron transitions connect baryon and lepton number, we need to consider both the baryon number current and lepton number current that couple to the background field. It is convenient to rewrite B and L currents in terms of the $B+L$ and $B-L$ currents. From Eq. (1), we know that

$$\frac{n_{B-L}}{s} = \frac{\mu_-^0(T_-)}{g_{*s}T_-} = \frac{g_-a_0(T_-)}{g_{*s}T_-}\,, \qquad \frac{n_{B+L}}{s} = \frac{\mu_+^0(T_+)}{g_{*s}T_+} = \frac{g_+a_0(T_+)}{g_{*s}T_+}\,, \quad (2)$$

where T_- and T_+ are the lowest freeze-out temperature for any interactions that could violate $B-L$ and $B+L$, respectively. T_+ is the sphaleron freeze-out temperature which is roughly 150 GeV. T_- ranges from TeV to GUT scale and is very model dependent. Notice that $T_- \ll T_+$, so whether $n_{B+L} \ll n_{B-L}$ or $n_{B+L} \gg n_{B-L}$ will only depend on whether $\mu^0(T)/T$ is an increasing or decreasing function with respect to $1/T$. The net baryon number $n_B = (n_{B+L} + n_{B-L})/2$, so we know that n_B is of the same order as $\max\{n_{B+L}, n_{B-L}\}$. From Eq. (2), we get

$$\frac{n_B}{s} = \begin{cases} \dfrac{n_{B+L}}{2s} \sim \dfrac{g_+a_0(T_+)}{g_{*s}T_+} & \text{if } \dfrac{|\mu^0(T)|}{T} \text{ increases as a function of } 1/T, \\ \dfrac{n_{B-L}}{2s} \sim \dfrac{g_-a_0(T_-)}{g_{*s}T_-} & \text{if } \dfrac{|\mu^0(T)|}{T} \text{ decreases as a function of } 1/T. \end{cases} \quad (3)$$

3. Present-day constraints on Lorentz violation

In principle, there are no real experimental constraints as baryogenesis happens at the early time while all experiments are at present. Nevertheless, the highly constrained experimental bounds today suggest that the spontaneous Lorentz-violating background undergoes a phase transition if it doesn't decay away or roll to an extremely small value.

The direct constraints between baryon number current and Lorentz violating background field are coming from neutral meson mixing. Only

the difference Δa_μ between the corresponding two a_μ coefficients is observable. The experimental constraint comes from the parameter $\Delta a_\mu = r_{q_1} a_\mu^{q_1} - r_{q_2} a_\mu^{q_2}$, where $a_\mu^{q_1}$, $a_\mu^{q_2}$ are Lorentz-violating coupling constants for the two valence quarks in the meson, and where the factors r_{q_1} and r_{q_2} allow for quark-binding or other normalization effects. Experiments studying neutral K-mesons have constrained two combinations of Δa for d and s quarks, with bounds in the Sun-centered frame of approximately

$$|\Delta a_0| \leq 10^{-20} \text{ GeV} \tag{4}$$

by the KTeV Collaboration at Fermilab [10,11]. Other experiments with D mesons have constrained two combinations of Δa for the u and c quarks at about 10^{-15} GeV (FOCUS Collaboration, Fermilab) [10,12]. There are even more constrained results from axial vector current and astrophysics, but the couplings in those constraints are essential to generate baryons.

4. Sources of Lorentz violation

We first consider that Lorentz-violating vector field A_μ has a constant expectation value in the vacuum (a_0 = constant). Our discussion could also be generalized to a ghost field and high rank-tensor condensate[2]. The vector condensation is achieved through a Mexican-hat potential[a] $V(A_\mu) = \frac{\mu^2}{2} A_\mu A^\mu + \frac{\lambda}{4}(A_\mu A^\mu)^2$. At the classical level, the timelike component for a vector field with minimal ground state energy is given by ${a_0}^2 = \frac{\mu^2}{\lambda}$. Since $\mu^0/T = g a_0/T$ is increasing as the universe expands (and T decreases), the relevant freeze-out temperature is thus $T_+ = 150$ GeV, due to sphaleron transitions. From Eq. (1) we obtain

$$\frac{n_B}{s} \sim \frac{g a_0}{g_{*s} T_+} \sim g a_0 (10^4 \text{ GeV})^{-1} \approx 10^{-10} \,. \tag{5}$$

Such a field condensate would seem to violate the experimental constraints discussed in Section 3. One way to accomodate the experimental limits is to imagine a phase transition for the A_μ field itself. We can replace the coefficient of the mass term μ^2 with $({\mu'}^2 - \alpha|\Phi|^2)$ in the potential, where Φ is the Higgs doublet. At high temperatures, the Higgs expectation value $\langle\Phi\rangle$ vanishes, and we get a non-zero vacuum expectation value of the vector background field. At late times, $|\Phi|^2 = v^2$. If $\mu'^2 - \alpha v^2$ is negative, we get a zero vev for vector background field. So the Lorentz symmetry is restored.

[a] Notice we use the minus metric here.

Another possibility is that the Lorentz-violating background is time-dependent. A simple way to achieve this is to image A_μ is the gradient of a slowly-rolling scalar field ϕ. The chemical potential term a_0 is then given by $\dot{\phi}/f$. When one applies this to a quintessence field which has "tracking" behavior, $\dot{\phi} \propto \sqrt{V(\phi)} \propto \sqrt{\rho_{\rm back}} \propto T^2$. We can see that the freeze-out temperature is determined by T_-, which is very model dependent. Similarly, one can consider the interaction between the derivative of the Ricci scalar curvature $\mathcal{R}$ and the baryon number current J^μ from the effective theory of gravity[8] $\frac{1}{M_*^2}\int d^4x\sqrt{-g}(\partial_\mu \mathcal{R})J^\mu$. The net baryon number density obtained is proportional to an even higher positive power of freeze-out temperature T_F, since $\dot{\mathcal{R}} \propto \dot{\rho}$, where ρ is the total energy density.

Finally we consider the Lorentz-violating background arising as the gradient of a pseudo-Nambu-Goldstone boson (PNGB) $\phi = f\theta$, where f is the scale of spontaneous symmetry breaking. A PNGB remains overdamped in its potential until its mass becomes comparable to the Hubble parameter, at which time it will roll to its minimum and begin to oscillate and decay like a massive particle. If we want to generate a baryon asymmetry of the right amplitude, then from $n_B/s \sim \dot{\phi}/fg_{*s}T_F = 10^{-10}$ and $g_{*s} \sim 100$ we require $\dot{\phi} = 10^{-8} fT_F$. The PNGB obeys the equation of motion $\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$ and we drop the term $\ddot{\phi}$ as we are interested in the rolling phase. For typical values $\phi \sim f$, we have $\dot{\phi} \sim H^{-1}\frac{dV}{d\phi} \sim m^2 fM_{pl}/T^2$. Thus, to achieve successful baryogenesis requires that the freeze-out temperature satisfy $\frac{T_F^3}{m^2} \sim 10^8 M_{pl}$. The ideal circumstance would be if freeze-out occured when the field had just begun to roll substantially, but not yet begun to oscillate. This corresponds to $H \sim m$, which implies $T_F^2 \sim mM_{pl}$. Comparing to the expression of $\dot{\phi}$ shows that PNGB baryogenesis works if the freeze-out temperature is at an intermediate scale $T_F \sim 10^{-8}M_{pl} \sim 10^{10}$ GeV and the PNGB mass is $m \sim T_F^2/M_{pl} \sim 100$ GeV.

5. Conclusion

We have investigated the possible origin of the observed baryon asymmetry in the presence of a coupling between a Lorentz-violating vector field and the baryon current, and especially reconsidered the effects of sphaleron transitions. If a_0/T is increasing with time, then the final net baryon number density is determined by the freeze-out temperature $T_+ \approx 150$ GeV. For the opposite case, the final net baryon number density is determined by the freeze-out temperature T_- which is model-dependent. Most previous works [2,3,4,5,8] consider a slow rolling scalar field as the spontaneous

Lorentz-violating background, and the absolute value of the effective chemical potential is decreasing with time, so the right net baryon number density generated depends on a high freeze-out temperature T_{-}. In order to obtain the right net baryon number density, the coupling times the time component of the background field ga_0 should be not too small, and experimental constraints at present suggest that we need some dynamical mechanism to decrease a_0. We first consider a constant Lorentz-violating background case and sphaleron transitions will be the main source to generate the baryon asymmetry. We can imagine that a phase transition occurs in between freeze-out and today. Our investigation of the PNGB scenario reveals that the most natural implementation of this idea requires PNGB's with weak-scale masses (100 GeV) and $(B-L)$-violating interactions that freeze out at an intermediate scale of around 10^{10} GeV naturally from the decay of Majorana neutrinos. We therefore consider this scenario to be quite promising.

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